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Ulcerative colitis and autoimmunity induced by loss of myeloid αv integrins

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Contributed by Richard O. Hynes, August 7, 2007 (sent for review July 25, 2007)

The gastrointestinal tract is constantly challenged by foreign antigens and commensal bacteria but nonetheless is able to maintain a state of immunological quiescence. Recent advances have highlighted the importance of active suppression by regulatory lymphocytes and immunosuppressive cytokines in controlling mucosal immunity. Failures of these mechanisms contribute to the development of inflammatory bowel disease, but how these regulatory networks are established remains unclear. Here, we demonstrate key roles for αv integrins in regulation of mucosal immunity. We report that deletion of αv in the immune system causes severe colitis, autoimmunity, and cancer. Mice lacking immune cell αv have fewer regulatory T (Treg) cells in the colon and corresponding increases in activated T cells and T cell cytokine production, leading to colitis. Using conditional gene targeting, we demonstrate that this is specifically attributable to loss of αv from myeloid cells. Furthermore, we show that gut-associated macrophages and dendritic cells fail both to remove apoptotic cells efficiently and to induce Treg cells. Our results identify a vital role for myeloid αv integrins in generating mucosal Treg cells and emphasize the importance of antigen-presenting cells in establishing immune tolerance.

immunoregulation | phagocytosis | apoptotic | dendritic cell | regulatory T cell

Integrins are dimeric cell-surface receptors composed of α and β subunits (1). αv is the most promiscuous α subunit, associating with five different β subunits ($\beta 1$, $\beta 3$, $\beta 5$, $\beta 6$, and $\beta 8$) and participates in many important cellular processes, including cell adhesion, migration, survival, and growth factor signaling. αv integrins are expressed in many tissues throughout development, and αv knockout mice die at midgestation from placental deficiencies or, immediately after birth, with cerebral and intestinal hemorrhage and cleft palate (2). The lethality of $\alpha\text{v}^{-/-}$ mice is attributable mainly to loss of $\alpha\text{v}\beta 8$, because $\beta 8^{-/-}$ mice show similar placental and neural vasculature abnormalities (3), and these defects are principally attributable to loss of $\alpha\text{v}\beta 8$ from parenchymal tissues supporting blood vessels (4, 5). Knockouts of most other αv -associated β integrins ($\beta 3$, $\beta 5$, and $\beta 6$) are viable and reveal roles for αv in repair of tissue injury, inflammation, and immune responses (1, 6–8). $\alpha\text{v}\beta 6$ and $\alpha\text{v}\beta 8$ are expressed in epithelium, where their functions include binding and activating TGF- β (9), and $\alpha\text{v}\beta 8$ is also expressed by myeloid cells and T cells (10, 11). $\alpha\text{v}\beta 3$ and $\alpha\text{v}\beta 5$ are more widely expressed and are up-regulated by many cells after tissue injury. In the immune system, $\alpha\text{v}\beta 3$ and $\alpha\text{v}\beta 5$ are expressed by many different cell types and promote cell adhesion, migration, and survival. αv integrins also mediate the uptake of apoptotic cells (12–14), a process central to immune regulation and inflammation resolution (15).

Here, we report that αv integrins are central to the normal regulation of immune responses in the intestine and that deletion of αv in the immune system leads to spontaneous colitis, wasting,

and autoimmunity. Colitis is associated with activated T cells, high expression of T cell cytokines, and corresponding loss of tissue-resident regulatory T (Treg) cells. We dissect the contribution of αv on different immune cell populations, identifying myeloid cells [macrophages, dendritic cells (DCs), and/or neutrophils] as the critical expressers of αv integrins. We further show that deletion of αv leads to impaired removal of apoptotic cells and failure of mesenteric lymph node (mLN) DCs to generate Treg cells.

Results

Mice Lacking αv Integrins Develop Colitis. Determining the precise contributions of αv integrins to immune functions *in vivo* has been limited by the lethal phenotype of αv knockout mice, which die from vascular and developmental defects (2). To circumvent this problem, we generated a conditional knockout of αv ($\alpha\text{v}^{\text{flox/flox}}$ mice) [supporting information (SI) Fig. 7], which was crossed with αv -knockout heterozygous mice ($\alpha\text{v}^{+/-}$) and tie2-CRE transgenic mice (16) to generate αv -tie2 and control mice ($\alpha\text{v}^{\text{flox/+}}$;tie2-cre⁺ and $\alpha\text{v}^{\text{flox/+}}$;tie2-cre⁺, respectively). Tie2-CRE transgenic mice express CRE in endothelial cells and hemangioblasts, leading to gene deletion specifically in endothelial and hematopoietic cells (17) (Fig. 1 *a* and *b* and SI Fig. 7), which was confirmed for both the floxed αv allele and αv protein (Fig. 1 *c* and *d*).

αv -tie2 mice were born at expected frequency and developed normally with no evidence of defects in angiogenesis or development of hematopoietic cells (4) (SI Figs. 8 and 9). However, from 12 weeks onward, αv -tie2 mice lost weight and body condition compared with controls and died prematurely (median lifespan of 44 weeks, $n = 42$, compared with >80 weeks for littermates, $n = 58$) (Fig. 2 *a* and *b*). Many αv -tie2 mice died after acute constriction of the intestine (Fig. 2 *d*), suggesting that defects in intestinal immunity underlie the wasting and death. Despite these areas of constriction appearing throughout the intestine, no inflammatory infiltrates were seen in the small intestine. However, inflammation was seen in the colon and cecum of all αv -tie2 mice from 14 weeks onward, with infiltrates

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The authors declare no conflict of interest.

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Abbreviations: aTreg, adaptive regulatory T; DC, dendritic cell; mLN, mesenteric lymph node; RGD, arginine-glycine-aspartic acid; Treg, regulatory T.

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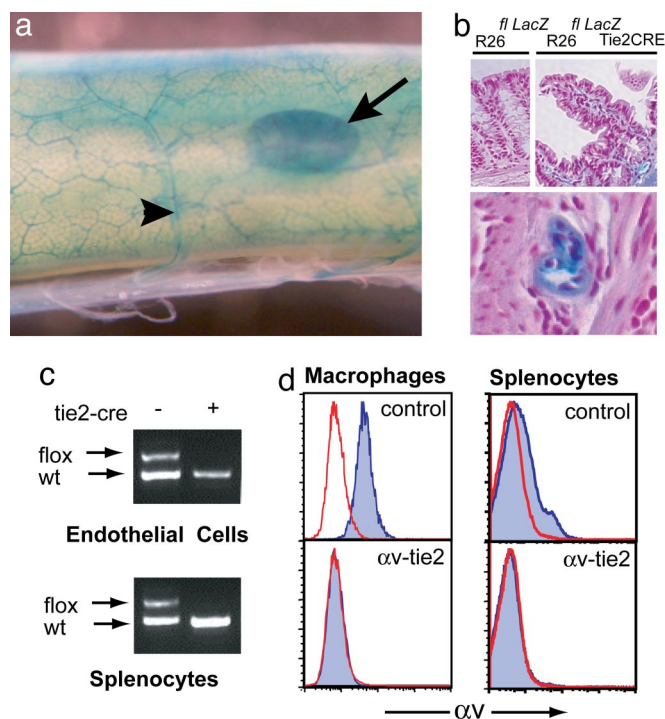


Fig. 1. Deletion of αv integrins in endothelial and hematopoietic cells in αv -tie2 mice. (a and b) Small intestine from tie2-CRE transgenic mice crossed to LacZ reporter mice, stained for LacZ activity. (a) CRE-mediated deletion in blood vessels and immune organs, indicated by an arrowhead and arrow, respectively. (b) Sections of stained tissue show CRE-mediated deletion in endothelial cells in vessels from control and reporter mice (Upper) and a single blood vessel from reporter mice at higher magnification (Lower). (c) PCR across exon 4 of αv gene in DNA from sorted lung endothelial cells (CD31⁺ cells) or splenocytes from mice carrying one floxed and one nonfloxed allele for αv show that the floxed allele is lost when mice also carry the tie2-CRE transgene. (d) FACS analysis of macrophages and total splenocytes from control (αv flox^{+/+}; tie2-CRE⁺) or αv -tie2 mice stained for surface expression of αv . Red lines show staining with isotype control antibody, and blue-filled histograms show staining for αv .

of lymphocytes, monocytes, and plasma cells (Fig. 2c and e–h). Inflammation was chronic and progressive, leading to ulcers, acute inflammatory infiltrates, and crypt abscesses by 20 weeks and extensive epithelial proliferation, regeneration, and adenocarcinoma from 40 weeks onward (Fig. 2h and SI Fig. 10). Inflammation was also found in the peritoneum, in the liver, and, in $\approx 40\%$ of mice, in the nasal cavity and respiratory tract (SI Fig. 10).

Immune Cell Activation in αv -tie2 Mice. Histology of the colon suggested that the main effector cells mediating inflammation were T cells, and hence we looked for evidence of T cell activation. The mLNs and Peyer's patches of αv -tie2 mice were enlarged compared with controls (Fig. 3a) and contained significantly higher proportions of activated (CD62L^{low} CD44^{high}) CD4⁺ T cells (Fig. 3B, Table 1, and SI Fig. 11). The spleen and peripheral lymph nodes (PLNs) also contained higher numbers of activated CD4⁺ cells in older mice (>12 weeks) (SI Fig. 11), although they did not demonstrate gross enlargement. Expression of the T cell cytokines IL4 and IFN- γ was increased both systemically and in the colon of αv -tie2 mice (Fig. 3c and Table 2). Other cytokines were also increased in the colon, including IL5, IL6, and TNF- α but not IL12 and IL23 (SI Fig. 11). Notably, T cell activation preceded inflammation, with enlargement of mLNs, T cell activation, and increased expression of IL4 and IFN- γ evident even at weaning (3 weeks; Tables 1 and 2),

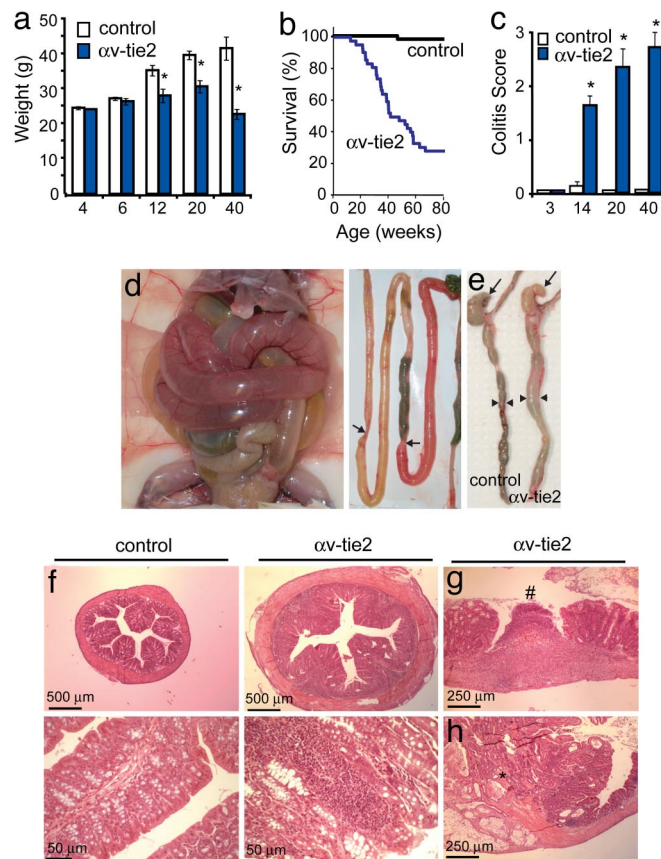


Fig. 2. αv -tie2 mice develop colitis. (a–c) Weight (a), survival (b), and colitis score (c) of αv -tie2 (blue bars/blue line) and littermate control (open bars/black line) mice. Weight and colitis scores are expressed as mean \pm SEM ($n = 3$ –13 mice per group; males only used for weight; similar results seen for females). *, $P < 0.01$. (d) Acute intestinal obstruction in αv -tie2 mouse (20 weeks of age). Arrows show points of constriction in small intestine. (e) Cecum and colon from αv -tie2 mice (40 weeks) are enlarged compared with those from control mice. The cecum is inflamed (arrows), and the colon is thickened (arrowheads). (f) Colons of 20-week-old αv -tie2 mice have thickened mucosal and submucosal layers with transmural inflammation. Infiltrates are predominantly lymphocytes and monocytes. (g and h) Ulcer (#) (g) and tumor (*) (h) in colons of 40-week-old αv -tie2 mice.

suggesting colitis arose from early loss of regulation of T cell responses.

Changes in Treg Cells in αv -tie2 Mice. The central importance of Treg cells in controlling mucosal inflammation is demonstrated in the many studies showing that, in their absence, effector T cells rapidly induce colitis and wasting (18). We therefore examined whether Treg cells were present in αv -tie2 mice. Two principal pathways give rise to Treg cells: “natural” Treg (nTreg) cells arise in the thymus, are found in lymphoid organs, and mediate tolerance to self-antigen, whereas “adaptive” Treg (aTreg) cells arise in the periphery and are thought to be the main mechanism for regulating responses to tissue-specific or foreign antigens, such as those derived from commensal bacteria (19). As determined by CD4⁺ CD25⁺ FoxP3⁺, equivalent numbers of Treg cells were found in spleens of controls and αv -tie2 mice, whereas the mLN of αv -tie2 mice contained increased proportions of Tregs as compared with controls (Fig. 3d). These cells are likely to be predominantly natural Tregs and appear to be generated in the absence of αv . In contrast with the results for spleen and mLN, the colons of αv -tie2 mice had significantly decreased numbers (50% reduction) of Treg cells compared with

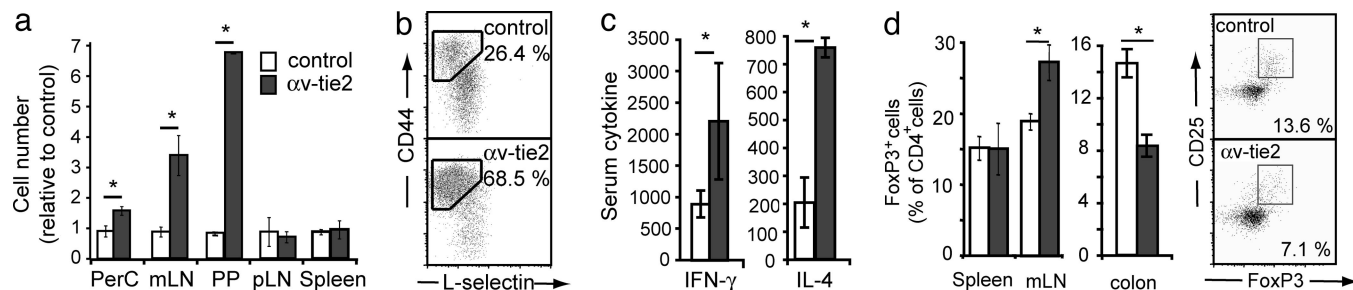


Fig. 3. Immune cell activation in $\alpha\nu$ -tie2 mice. (a) Total cell numbers isolated from peritoneal cavity (PerC), peripheral lymph nodes (pLN) and mLN, Peyer's patch (PP), and spleen of 12-week-old $\alpha\nu$ -tie2 and control mice. (b) FACS analysis of spleen cells from 12-week-old control and $\alpha\nu$ -tie2 mice, gated on CD4⁺ T cells, shows higher proportions of activated (CD44^{high} L-selectin^{low}) CD4⁺ cells in $\alpha\nu$ -tie2 mice. (c) Circulating cytokines from serum of $\alpha\nu$ -tie2 or control mice (aged 12 weeks). (d) Treg cells from indicated tissues from 8-week-old $\alpha\nu$ -tie2 and control mice. Data are expressed as percentage of CD4⁺ cells that are CD25⁺ FoxP3⁺. FACS data are representative of colon lymphocytes, gated on CD4⁺ cells. In all graphs, data are means \pm SEM for at least three mice per group. *, $P < 0.05$.

controls (Fig. 3d). These Treg cells are probably aTreg cells, suggesting that failure to generate these cells leads to loss of mucosal tolerance in *αv-tie2* mice.

Colitis Is Caused by Loss of $\alpha\nu$ from Myeloid Cells. The above data indicate that T cells are the main effectors of inflammation in $\alpha\nu$ -tie2 mice and suggest that this may be attributable to loss of colon Tregs. However, because Tie2-CRE causes deletion in both endothelial and hematopoietic cells (Fig. 1), these changes in T cells could either be attributable to direct effects of loss of $\alpha\nu$ from T cells or indirect effects after loss of $\alpha\nu$ from other cell types. We therefore carried out a series of experiments to test directly the importance of $\alpha\nu$ on T cells and other immune cells. Transplant of an $\alpha\nu$ -deficient immune system to lethally irradiated control mice resulted in weight loss and colitis (Fig. 4 *a* and *b*), and, conversely, reconstitution of old (24-week-old) $\alpha\nu$ -tie2 mice with control bone marrow reversed ongoing inflammation with restoration of normal colon histology (Fig. 4 *a* and *b*). Therefore, inflammation and colonic damage did not arise from defects in intestinal development or from loss of $\alpha\nu$ from endothelial cells, but were directly attributable to deletion of $\alpha\nu$ in the immune system.

We then generated four additional αv -flox CRE mouse lines to analyze contributions of αv on immune cell subpopulations. Mice lacking αv on T cells, B cells, or both T and B cells did not develop colitis despite efficient deletion of αv (Fig. 4 *c* and *d* and SI Fig. 12). In contrast, mice lacking αv on macrophages, neutrophils, and DCs [αv -LysM mice (20)] (SI Fig. 11) developed colitis closely resembling that from αv -tie2 mice, with similar histology and proinflammatory cytokine expression (Fig. 4 *c-f*). The incidence and severity of disease were lower in these mice than in αv -tie2 mice of the same age (30% severe colitis in αv -LysM at 40 weeks compared with 100% in αv -tie2), probably as a consequence of incomplete gene deletion (20) (50–80% gene deletion in αv -LysM mice compared with 100% in αv -tie2) (SI Fig. 12). Taken together, these data show that inflammation

does not arise from loss of αv on adaptive immune cells but instead indicate an important role for αv on myeloid cells in immune regulation.

Impaired Function of mLN DCs in α -*tie2* Mice. The dependence of colitis on deletion of α from myeloid cells raised the possibility that the loss of colon Treg cells was attributable to defects in DCs. We therefore tested the ability of α -deficient DCs to generate aTreg cells. Culture of bone marrow DCs with CD4⁺ CD25⁻ T cells generated \approx 5% Treg cells regardless of α expression by the DCs (Fig. 5a). However DCs from mLN of α -*tie2* mice generated fewer (1% compared with 4–5%) CD4⁺ CD25⁺ FoxP3⁺ T cells than DCs from control mice (Fig. 5a). These results show that mucosal DCs but not bone marrow-derived DCs from α -*tie2* mice are impaired in their ability to generate Treg cells. It is recognized that certain mLN DC subsets induce differentiation of T cells into Treg cells and that a specific population, marked by expression of CD103 (α E β 7 integrin), is implicated in imprinting gut-homing (21). CD11c^{high} CD103⁺ DCs were reduced in mLN of α -*tie2* mice (Fig. 5b), providing a potential explanation for the reduction in intestinal Treg cells.

Impaired Removal of Apoptotic Cells in $\alpha\text{v-tie2}$ Mice. Both $\alpha\text{v}\beta3$ and $\alpha\text{v}\beta5$ on macrophages and DCs have been implicated in the removal of apoptotic cells (11–13), a process known to contribute to regulation of inflammation and immune tolerance (14). Furthermore, phagocytosis of apoptotic cells reprograms macrophages and DCs to a tolerogenic phenotype, in part through $\text{TGF-}\beta$, and is associated with the production of Tregs (22). Macrophages derived from $\alpha\text{v-tie2}$ mice had impaired phagocytosis of apoptotic cells, comparable with that seen when αv blocking antibodies or ligand-mimetic peptide [arginine-glycine-aspartic acid (RGD)] were used (Fig. 6*a*). This was not attributable to defective differentiation of cells in the absence of αv , because deletion of αv from mature macrophages also resulted in inhibition of phagocytosis (Fig. 6*b* and [SI Fig. 13](#)). Further-

Table 1. Comparison of T cell activation in mLN αv -tie2 mice before (3 weeks) and after (12 weeks) onset of histologically evident colitis

	Cell number $\times 10^6$		Activated CD4 ⁺ T cells, %	
	3 weeks (<i>P</i> = 0.001)	12 weeks (<i>P</i> < 0.001)	3 weeks (<i>P</i> = 0.003)	12 weeks (<i>P</i> = 0.007)
Mice				
Control	7.1 \pm 0.23	8.6 \pm 1.6	11 \pm 1.3	15 \pm 0.81
α v-tie2	15 \pm 1.1	34.2 \pm 6.7	20 \pm 0.81	31.7 \pm 0.40

T cell activation was assessed by CD44 and L-selectin staining. *P* values are from Student's *t* test.

Table 2. Proinflammatory cytokine expression in colon of αv -tie2 mice before (3 weeks) and after (18 weeks) onset of histologically evident colitis

	IFN- γ		IL4	
	3 weeks ($P = 0.017$)	18 weeks ($P = 0.086$)	3 weeks ($P = 0.018$)	18 weeks ($P = 0.079$)
Mice				
Control	26 ± 4.7	26 ± 9.9	2.1 ± 0.58	1.3 ± 1.0
α V-tie2	326 ± 122	518 ± 236	268 ± 109	228 ± 105

Gene expression is relative to GAPDH, $\times 10^3$. *P* values are from Student's *t* test.

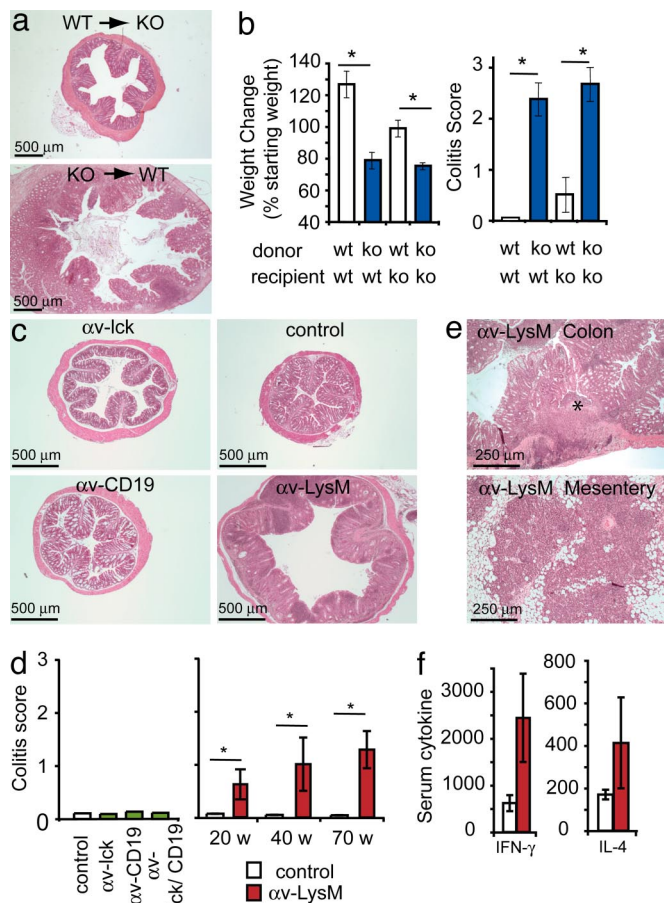


Fig. 4. Loss of α_v from myeloid cells (but not lymphocytes) causes colitis. (a and b) Representative histology of colon (a), weight (b), and colitis score (b) of mice after bone marrow transplantation between 3-month-old α_v -tie2 (KO) and control (WT) mice. Colitis was assessed a further 3 months after bone marrow transplantation. Note that transplantation of α_v -deficient bone marrow (KO \rightarrow WT) leads to colitis, whereas transplantation of control bone marrow is sufficient to reverse ongoing disease (WT \rightarrow KO). (c and d) Representative histology of colon (c) and colitis score (d) from indicated α_v -conditional knockout mice at 40–50 weeks of age. Deletion of α_v from T cells (α_v -lck) or from B cells (α_v -CD19) does not lead to colitis, whereas deletion of α_v from myeloid cells (α_v -LysM) does. (e) Detail of colon (Upper) and mesentery (Lower) from 70-week-old α_v -LysM mouse. Note ulceration in colon (*) and inflammation in mesentery. (f) Serum cytokine levels in 20-week-old α_v -LysM mice. All graphs are mean \pm SEM ($n \geq 4$ mice per group). *, $P < 0.05$.

more, macrophages lacking α_v were no longer sensitive to the inhibitory effects of RGD peptides (Fig. 6b). Similar phagocytic defects were seen in DCs derived from α_v -tie2 mice (Fig. 6c). To determine whether deletion of α_v affected phagocytosis *in vivo*, we carried out two further experiments. First, apoptotic cells were injected into the peritoneal cavity, and their internalization by macrophages were measured. Reduced phagocytosis was seen in both α_v -tie2 and α_v -LysM mice (Fig. 6d). Second, to assess the rate of removal of apoptotic cells from the intestine, we measured the number of uncleared TUNEL⁺ cells in the colons of control and α_v -tie2 mice at 6 weeks of age (before the onset of colitis). Twice as many apoptotic cells were seen in α_v -tie2 mice, consistent with reduced phagocytosis and apoptotic cell removal (Fig. 6e–f). A well recognized consequence of persistent apoptotic cells is the generation of autoantigens that, in turn, drive autoantibody production (23). We therefore determined whether mice lacking α_v had increased levels of autoantibodies. Serum from both α_v -tie2 and α_v -LysM mice contained high levels of autoantibodies, including antibodies to tropomyosin, an

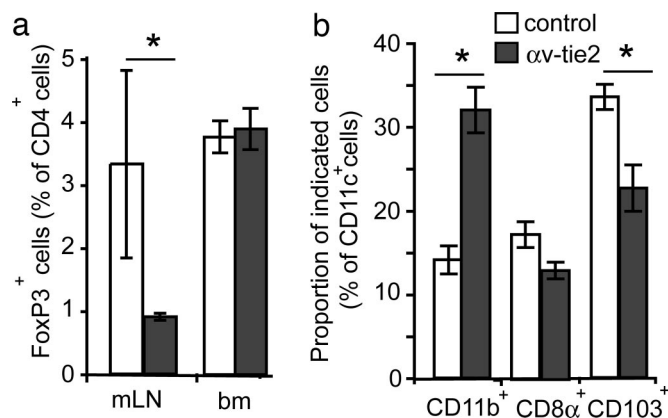


Fig. 5. DCs from mLN of α_v -tie2 mice have reduced ability to generate Treg cells. (a) Proportion of Treg cells generated from coculture of CD4⁺ CD25⁺ T cells with DCs purified from mLN or grown from bone marrow (bm) of control and α_v -tie2 mice. (b) Proportion of DC subpopulations in mLN of 10-week-old control and α_v -tie2 mice, expressed as percentage of CD11c^{high} cells. All graphs are mean \pm SEM ($n \geq 3$). *, $P < 0.05$.

autoantigen associated with colitis in humans (24), and antibodies to prominent components of dying cells, such as phosphatidylserine, dsDNA, and anti-nuclear antibodies (Fig. 6g–i).

Discussion

In summary, we have shown that α_v integrins are central to intestinal immune regulation and that deletion of α_v leads to colitis, autoimmunity, and cancer, thus establishing a mouse model for inflammatory bowel disease. The maintenance of mucosal immune homeostasis relies on the sampling of intestinal antigens by DCs and the subsequent production of aTreg cells that home to the intestine and regulate immune responses. Colitis in α_v -tie2 mice is likely to be caused by loss of these colon aTreg cells and corresponding increases in activated T cells and T cell cytokine production. This phenotype is attributable to loss of α_v from macrophages and DCs, which reduces phagocytosis of apoptotic cells and inhibits the generation of mucosal aTreg cells.

The generation and function of aTreg cells requires TGF- β signaling in and between T cells, and mice lacking TGF- β or TGF- β signaling components specifically in T cells have phenotypes resembling those of α_v -tie2 mice (25, 26). It is pertinent that α_v , when dimerized with β_6 and β_8 , binds and activates TGF- β (9). Loss of α_v -mediated TGF- β activation may therefore contribute to the α_v -tie2 phenotype, and we propose that DC-expressed α_v integrins locally activate TGF- β , which acts in a paracrine fashion to initiate Treg differentiation in T cells. Furthermore, our data suggest that TGF- β production by T cells is insufficient to regulate immune responses in the absence of TGF- β activation by antigen-presenting cells, providing a mechanism by which antigen specificity is retained in aTreg cells. The DCs that inhabit mucosal tissues appear particularly sensitive to the loss of α_v integrins because bone marrow-derived DCs generate Tregs normally in the absence of α_v . TGF- β is present at high levels in the intestine, and it is likely that α_v also contributes to TGF- β signaling during DC maturation, because TGF- β conditions DCs to generate aTreg cells. Furthermore, fewer mLN DCs from α_v -tie2 mice express CD103⁺ (α_E integrin), which is stimulated by TGF- β . We propose that absence of these DCs reflects, in part, failure of macrophages and DCs in the intestine to activate TGF- β .

Colitis is not seen in mice lacking β_3 , β_5 , or β_6 integrins or in hematopoietic β_1 knockouts (27), heavily implicating β_8 in control of mucosal immunity. Recent complementary condi-

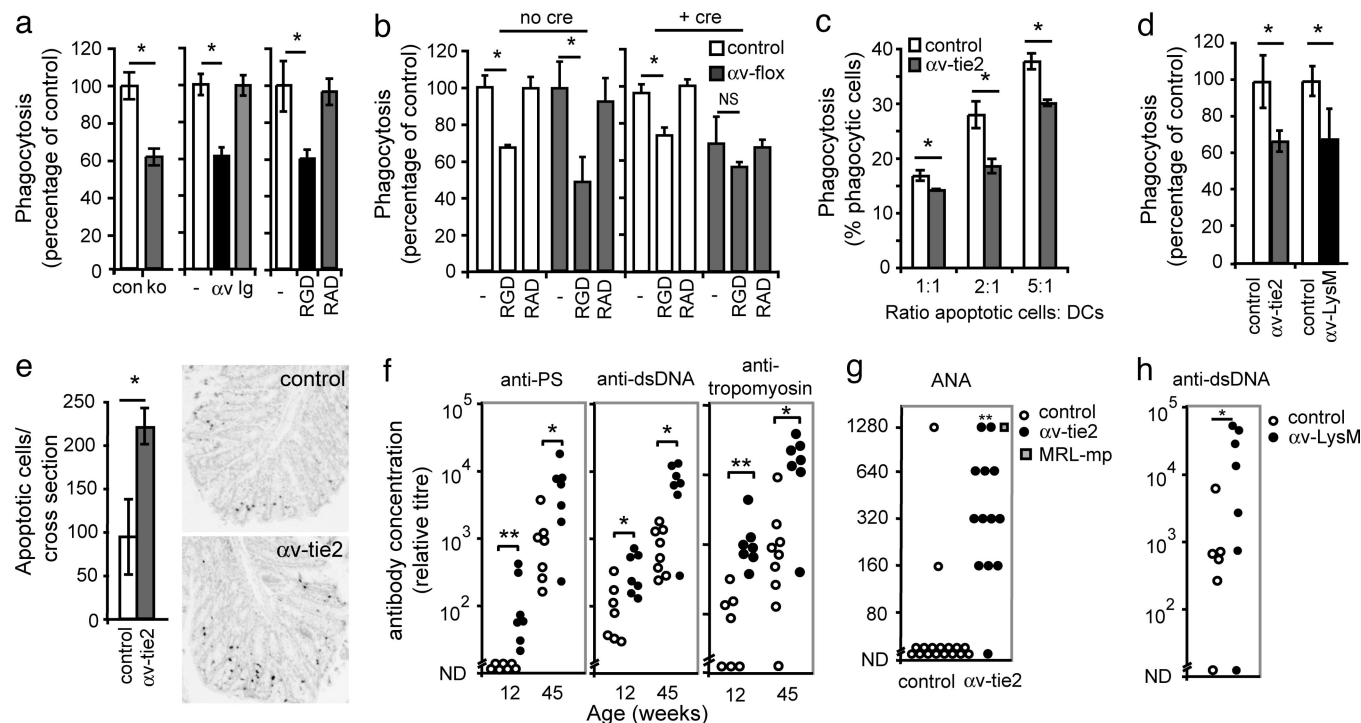


Fig. 6. αv integrins contribute to phagocytosis of apoptotic cells. (a) Phagocytosis of apoptotic cells (mouse thymocytes) by macrophages from control (con) or αv -tie2 mice (ko) or macrophages incubated with antibodies to αv integrins (αv), control Ig (Ig), RGD-containing peptides (RGD), or control peptide (RAD) (mean percentage phagocytic cells relative to untreated controls \pm SEM; $n \geq 3$). (b) Phagocytosis of apoptotic cells (human neutrophils) by macrophages from control or αv -floxed mice, untreated, or infected with adenovirus expressing CRE recombinase (MOI 100) (mean percentage phagocytic cells relative to untreated controls \pm SEM; $n \geq 3$). (c) Phagocytosis of apoptotic cells (mouse thymocytes) by DCs derived from bone marrow of control or αv -tie2 mice (mean percentage phagocytic cells \pm SEM; $n \geq 3$). (d) Phagocytosis of apoptotic cells (mouse thymocytes) instilled into the peritoneal cavity of control, αv -tie2, and αv -LysM mice. Data are percentage of recovered macrophages (F4/80⁺ cells) that had internalized apoptotic cells, expressed relative to control mice (mean \pm SEM; $n = 5$). Phagocytosis was assessed by microscopy (a and b) or FACS (c and d). (e) Apoptotic cells (TUNEL⁺ cells) in colonic mucosae of precolitic 6-week-old αv -tie2 and control mice. Data are from analysis of two colon cross-sections per mouse and ≥ 3 mice per group (mean \pm SEM). Shown are representative regions from control and αv -tie2 mice. (f) Autoantibodies in serum from control and αv -tie2 mice. (g) Antinuclear antibody (ANA) titers in serum from 45-week-old control and αv -tie2. Serum from autoimmune MRL-mp mice is included as a positive control. (h) Anti-dsDNA autoantibodies in serum of 70-week-old αv -LysM mice. In all graphs, *, $P < 0.05$; **, $P < 0.01$ (Student's *t* test for phagocytosis data, Mann-Whitney test for autoantibody titers).

tional knockout studies confirm this, showing that loss of $\alpha v\beta 8$ integrins from DCs but not from T cells also causes colitis (11). However, the phenotype of these mice is less severe than that seen in αv -tie2 mice, suggesting that loss of other αv integrins contributes to the severity of colitis. $\alpha v\beta 3$ and $\alpha v\beta 5$ have been implicated in the removal of apoptotic cells by macrophages and DCs, and αv -deficient mice have impaired phagocytosis of apoptotic cells, leading to persistence of dying cells in the colon. Apoptotic epithelial cells are thought to provide an important source of intestinal self-antigen, and DCs that exit the intestine bearing apoptotic cells express low levels of costimulatory molecules and are poor stimulators of T cell responses (28). Such “functionally immature” DCs have been shown to preferentially induce Treg differentiation when compared with classically activated DCs, and similar DCs can be induced *in vitro* by culture with apoptotic cells (29). Phagocytosis of apoptotic cells may therefore provide intestinal DCs with both antigen and the appropriate conditioning to generate Tregs. Impaired phagocytosis would lead to fewer DCs bearing apoptotic cells in the lymph nodes and potentially fewer Treg cells. The importance of this process in maintaining immune tolerance is demonstrated by genetic deletion of key components of the apoptotic cell-recognition machinery, which leads to persistent apoptotic cells, chronic inflammation, and development of autoimmune disease resembling systemic lupus erythematosus (15). These include mice lacking the serum protein MFG8/Lactadherin, which mediates apoptotic cell removal through αv integrins, implicat-

ing αv -dependent removal of apoptotic cells in the induction of immune tolerance (30). Hence, although phagocytosis defects may not be sufficient to induce the colitis seen in αv -tie2 and αv -LysM mice, they are likely to contribute to autoimmunity and inflammation. Intriguingly, many of the effects of apoptotic cell uptake have been attributed to the release of TGF- β , and it is tempting to speculate that uptake of apoptotic cells, synthesis of active TGF- β , and generation of Tregs are causally linked (31). In support of this possibility, systemic administration of large numbers of apoptotic cells promotes Treg expansion through TGF- β production (22), a process critically dependent on both macrophages and DCs.

We therefore propose a model of mucosal tolerance in which αv integrins have a dual role: $\alpha v\beta 3$ and $\alpha v\beta 5$ would mediate uptake of apoptotic cells by macrophages and DCs, thus providing self antigen and modifying the extent of inflammation, and $\alpha v\beta 8$ would generate Treg cells through local activation of TGF- β and conditioning of DCs (SI Fig. 14). The results presented here and our proposed model emphasize the vital role of antigen-presenting cells in regulation of inflammatory responses and maintenance of immune tolerance. Furthermore, these studies demonstrate the pleiotropic role of αv integrins in the regulation of mucosal immune responses and provide insights into mechanisms that control inflammatory bowel disease.

Methods

Mice. Generation of mice is described in SI Text. All mice used in the study were of mixed 129:C57BL/6:FVB background and

were housed under specific pathogen free conditions at Massachusetts Institute of Technology. Animal experiments were performed under appropriate licenses within local and national guidelines for animal care.

Analysis of Colitis. Representative longitudinal and cross-sections of large intestine were stained with hematoxylin and eosin and graded by using a scheme based on that described by Powrie and colleagues (32), as follows: 0 = normal; 1 = mild epithelial hyperplasia, mild mucosal inflammation; 2 = moderate hyperplasia, mucin depletion, moderate inflammation; 3 = severe hyperplasia, transmural inflammation, ulceration. The highest score seen in sections from the length of the colon and cecum was reported for each mouse. All scoring was on coded samples and independently confirmed by two pathologists (M.B. and R.T.B.).

Immune Analysis. Cell preparation and staining are described in *SI Text*. Serum cytokines were measured by *in vivo* cytokine capture assay. All autoantibody titers were determined by ELISA (*SI Text*) except antinuclear antibodies, which were from staining of HEP-G2 cells.

Treg Cell Generation. CD11c⁺ DCs were sorted from mLN or spleen by using CD11c microbeads (Miltenyi Biotec, Auburn, CA) and were routinely >85% CD11c⁺ cells after sorting. CD4⁺

CD25⁺ T cells were sorted from spleen suspensions by enrichment of CD4⁺ cells followed by depletion of CD25⁺ cells, using MACs microbeads (Miltenyi Biotec). A total of 10⁵ T cells were cultured with 2–5 × 10⁴ DCs in the presence of 0.5 μg/ml anti-CD3 antibody for 3 days, and the proportion of CD4⁺ CD25⁺ FoxP3⁺ cells was measured by FACS.

Phagocytosis Assays. Bone marrow-derived macrophage and DC culture, apoptotic cell generation, and phagocytosis assays are described in refs. 29 and 33. For αv blockade, anti-αv (H9–2B8), control Ig (E36–239) (50 μg/ml; both BD Biosciences Pharmingen, San Diego, CA), glycine-RGD-serine, or glycine-RAD-serine (0.5 mg/ml; both Calbiochem, San Diego, CA) were incubated with macrophages for 20–30 min before and throughout phagocytosis assays. For *in vivo* phagocytosis, 10⁷ fluorescently labeled apoptotic thymocytes were injected into the peritoneal cavity, and phagocytosis were assayed after 20 min by FACS of F4/80-stained lavages.

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